Small-Scale HVDC Assessment

Anchorage Association for Energy Economics
November 5th, 2012

Jason Meyer
Alaska Center for Energy and Power, UAF
Sohrab Pathan
Institute of Social and Economic Research, UAA

Small-Scale High-Voltage Direct Current Assessment

This presentation reflects the draft findings of a report to the Denali Commission by the Alaska Center or Energy and Power reviewing the Polarconsult HVDC Phase II project and providing conclusions and recommendations for future work on small-scale HVDC in Alaska. These draft findings are still undergoing internal and peer review. These findings are not final until published. Final report will be released December, 2012.

Polarconsult HVDC Project

- Goals:
  - Develop low-cost small-scale HVDC converter technology
  - Develop innovative transmission infrastructure
- Overall project and transmission infrastructure developed by Polarconsult
- Converter technology developed by Princeton Power
- Three phase project. Phases I and II are complete, Phase III is seeking funding.

Relevant Organizations

- Denali Commission
  - Project funder
- Polarconsult
  - Project lead
- Alaska Center for Energy and Power
  - Managing project
- Institute of Social and Economic Research
  - Joint position with ACEP for this project
- Princeton Power
  - Converter technology developer

HVDC Background Information

$P_{TRAN} = IV,\ P_{LOSS} = I^2R$

- $P_{LOSS} = (P_{TRAN}{}^2 R) / V^2$
- If V doubles, the line loss decreases by one fourth, and so on.
- High voltage transmission is necessary to keep losses from becoming prohibitively high.
- At greater distances, DC transmission generally has lower overall losses than AC transmission at comparable voltages.

HVDC Background Information

- Potential reasons for using HVDC
  - Bulk power
  - Long distances
  - Elimination of reactive power loss
  - Connecting asynchronous grids
  - More energy transfer per area right-of-way
  - Cable(s) needed
  - Minimize environmental impact
  - Integration with existing infrastructure

HVDC Background Material

- Potential reasons for not using HVDC
  - High cost of conversion equipment
  - Transformation and tapping power is not easy or possible
  - Possible harmonic inference with communication circuits
  - Ground currents (electrode)
  - High reactive power requirements at each terminal
  - Lack of skilled “specialty” workforce

HVDC Background Info

- Three primary vendors
  - ABB
  - Siemens
  - Alstom
- Line Commutated Converters (LCC) is established technology
  - Thyristor switches
- Voltage Source Converters (VSC) is new, rapidly evolving technology
  - Insulated Gate Polar Transistors (IGBTs)

Economic Considerations

- Added cost of converters (rectification and inversion)
- Savings in HVDC power transmission are realized in the reduced cost of the lines and their associated infrastructure
- Reduced power loss
- System cost difficult to estimate

HVDC Background Information

	Converter Type	Power Range, MW	Voltage Range, kV	Usage Today
"Traditional" HVDC	LCC	≈100s-1000s	≈10s-100s	Broad usage; stable technology
"Mid-Scale" HVDC:	VSC + IGBT	≈10s-1000s	≈10s-100s	Quickly growing usage; rapidly evolving technology
"Small-Scale" HVDC:	VSC + IGBT or ??	≈1s	≈10s	Not yet in use; technology under development

HVDC Background Information

- Commercial “Mid-Scale” HVDC
  - HVDC Light, by ABB
  - HVDC PLUS, by Siemens
  - HVDC MaxSine, by Alstom
- No Commercial “Small-Scale” HVDC
  - Limited research and development
  - Relevant industry application (Navy, trains, etc)

Multi-Terminal Networks

- Multi-terminal (or ‘multi-node’) grid is nontrivial, but possible with currently existing technology
  - Combining economic power to exploit a resource that is unaffordable to an isolated grid
  - Connecting a grid that uses a renewable, but intermittent, power source (such as solar or wind), to one that uses a steady source
  - Connection to extra power supply in case of failure
  - Increasing overall energy availability among otherwise isolated power grids
- VSC much more favorable over LCC

Single-Wire Earth Return (SWER)

- Transmit power using a single wire for transmission, and using the earth (or water) as a return path.
- Cost reduction, reduces environmental impact
- Voltage difference imposed on ground
  - Step potential
  - Corrosion
  - Interference with Functionality
- Capital costs for installation of a SWER line can be as low as half those of an equivalent 2-wire single-phase line

SWER Global Application

- Typically used where cost reduction is a high priority and there is limited underground infrastructure
  - Australia (124,272 miles)
  - New Zealand (93,000 miles)
  - Manitoba (4,300 miles)
- Canada, Botswana, India, Vietnam, Burkina Faso, Sweden, Mozambique, Brazil, Namibia, Zambia, Tunisia, South Africa, Mongolia, Cambodia, Laos

SWER Historic Alaskan Application

- Bethel – Napakiak (1980 - 2009)
  - 10.5-mile, 14.4 kV AC
  - Construction cost was $63,940 per mile (2012 dollars)
  - Eventual reliability issues and pole deterioration
  - Replaced with traditional pile foundation-supported poles and conventional 3-phase AC for $313,000 per mile (2012 dollars)
- Kobuk – Shungnak (1980 - 1991)
  - Experimental pole design (x-shaped)
  - Replaced with conventional 14-kV, 3-phase AC line

SWER Future Alaskan Application

- National Electrical Safety Code (NESC), which is established by IEEE, does not currently allow SWER on a system-wide basis, except in emergency situations and as a backup to the traditional line in case of failure.
- Alaska Department of Labor has been monitoring HVDC project, and has indicated that site-specific waivers MAY be issued. More research is needed.

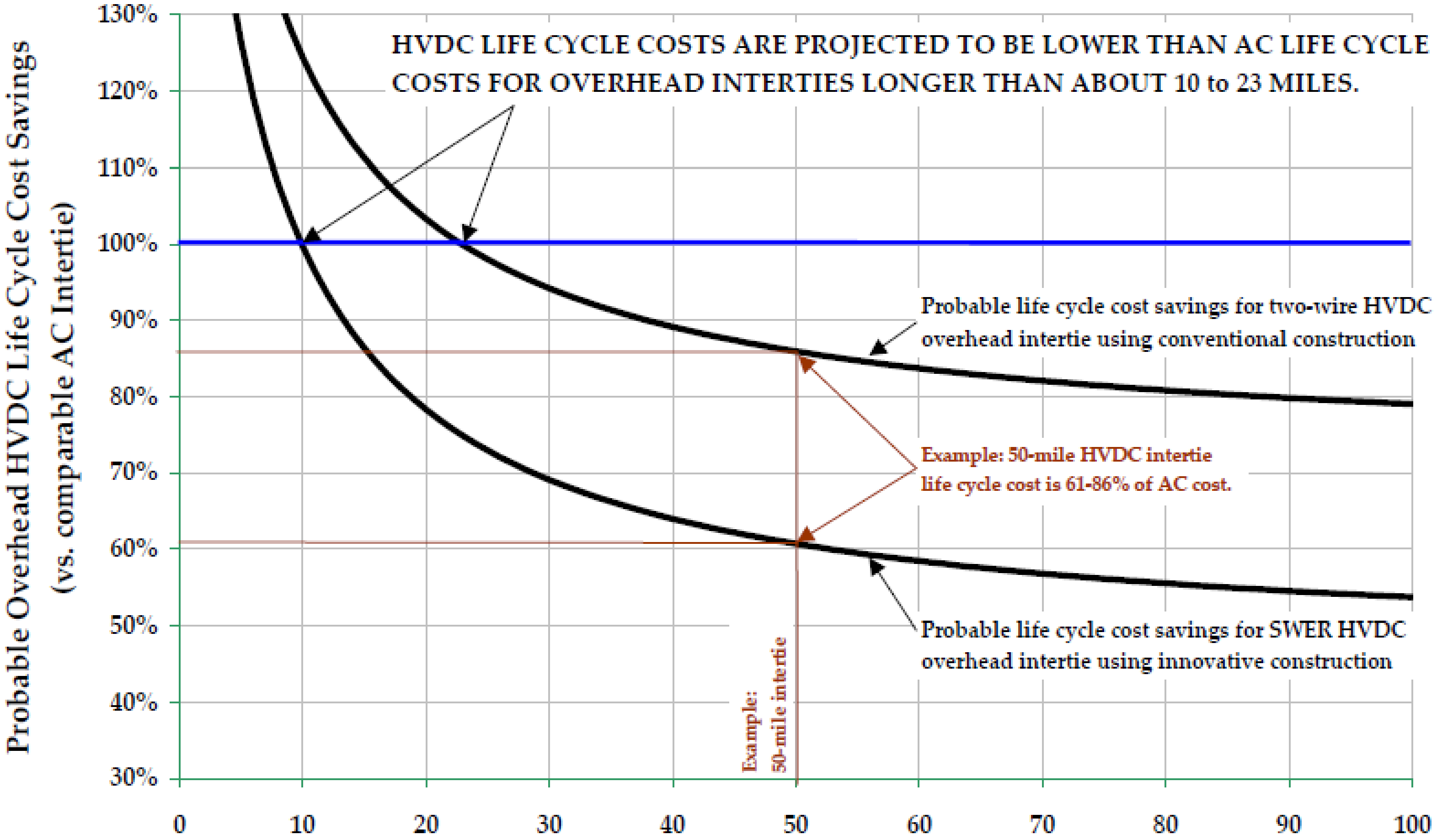
Phase I Overview

- Goals:
  - Evaluate the technical feasibility of the HVDC converter technology through a program of design, modeling, prototyping, and testing.
  - Evaluate the technical and economic feasibility of the overall system and estimate the potential savings compared to an AC intertie.
- Funded by the Denali Commission
- Managed by the Alaska Village Electric Cooperative
- Phase I was completed in 2009

Phase I Overview

Phase I Overview

Figure 5-2: Comparative Probable Life-Cycle Costs of HVDC Interties vs. AC Interties



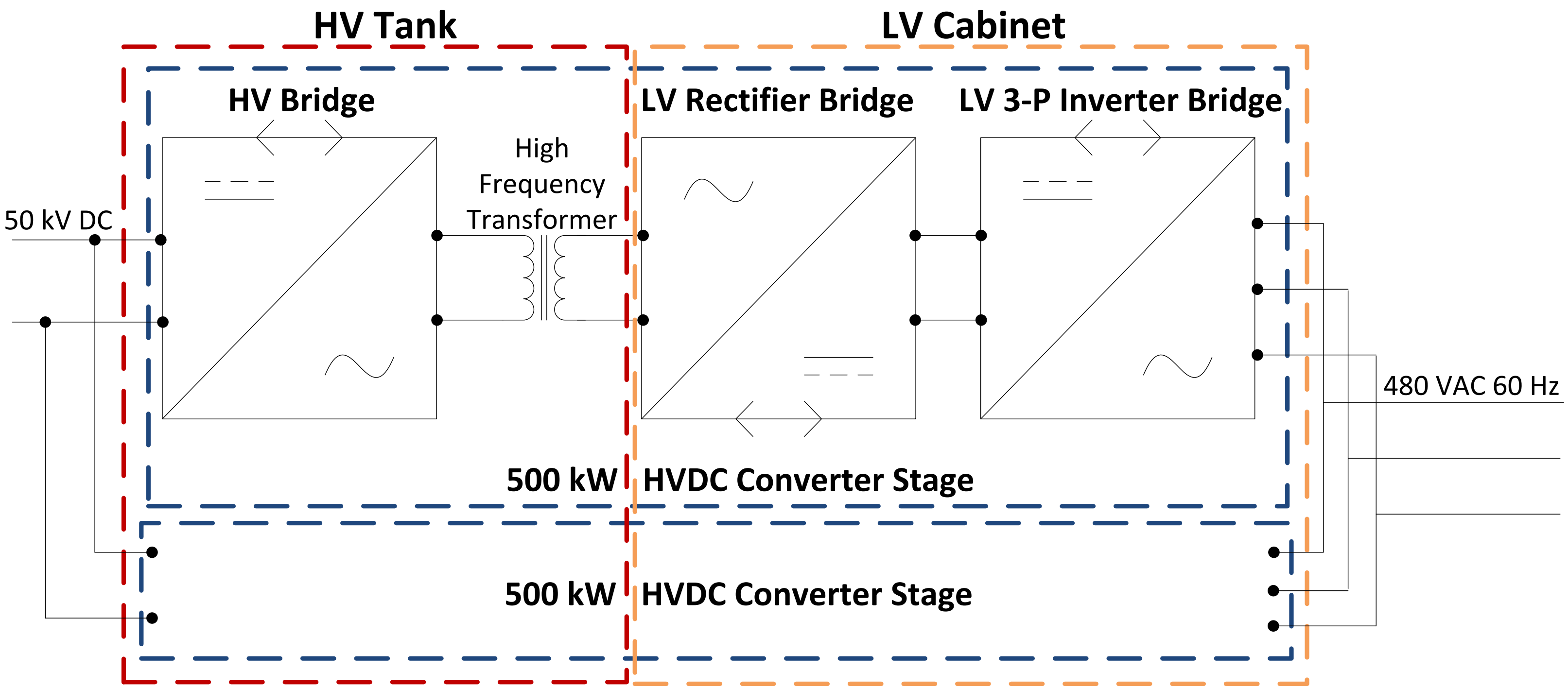
Phase II Overview

- Goal:
  - Complete full-scale prototyping, construction, and testing of the HVDC converters and transmission system hardware to finalize system designs, construction techniques, and construction costs.
- Funded by the Denali Commission under the EETG program
- Managed by ACEP
- Phase II completed May 2012

Princeton Power Converter

- Convert three-phase 480 VAC at 60 Hz to 50 kV DC for HVDC transmission and vice versa.
- Bi-directional meaning that power can flow in either direction working as either a rectifier or an inverter.
- Can operate in one of two modes depending on the direction of power flow and the state of each AC grid as follows:
  - Current source converter (CSC) in grid-tied mode regulating current to a village load, or
  - Voltage source converter (VSC) in microgrid mode regulating the AC system voltage.

Princeton Power Converter



Converter Demonstration

Converter Demonstration

Converter Demonstration

- Leakage along a taped seam on the cylindrical core insulation wrap of the high frequency transformer causing an arc during open air hi-pot testing at 11 kV.
- Loss (noise) in the optical triggering system for the IGBT switches in the high voltage tank causing timing issues.
- Thermal runaway of the IGBTs in the high voltage tank at 8 kHz switching frequency.

Prototype Pole Testing

Prototype Pole Testing

- Pole is instrumented to detect subsidence, frost jacking, load and stress changes, etc
- Will be monitored for two years by Polarconsult
- Concerns with fiberglass poles:
  - Ability for field crew to provide maintenance and repair to system
  - UV and cold weather

Phase III Overview

- Polarconsult is seeking funding for Alaska-based laboratory and field demonstration of converter units
- Converter IGBT issues are being addressed

General Findings

- HVDC is a mature and stable technology. However, the power scales on which it is currently available are inappropriate for small-scale Alaskan applications.
- Multi-terminal networks may be very useful for Alaskan applications. Princeton Power technology, given VSC configuration, is well-suited for that. However, the added complexity involved in a multi-terminal network should be considered before adoption.

SWER Findings

SWER is widely deployed internationally however its use in permafrost has thus far been limited.

- When SWER is deployed, return path must be beneath any permafrost, in thawed ground that is both electrically and mechanically stable.
- Proper grounding must be assured.
- Ground fault detection must be excellent; faults must trip fusing or relaying.
- Linemen must be properly trained to understand SWER.
- Climate change needs to be considered, from the perspective of both electrical and mechanical performance.

Economic Findings

The cost of a transmission line, whether it is AC or HVDC, depends on many factors including

- the distance between the power generating community and the power receiving community
- construction factors such as the logistics of the site and the terrain where the line will be constructed, and
- weather conditions that govern the design criteria for the system

Using unit cost, 60 miles, 69 kV

AC Intertie and Substation Costs	
Pre-construction	$5,604,000
Administration/Management	$2,380,000
Materials	$4,260,000
Shipping	$1,903,000
Mobilization/Demobilization	$7,198,000
Labor	$6,660,000
Additional Cost due to Difficult Terrain	$1,631,000
Construction of Substations (both sides of the line)	$3,000,000
Contingency	$6,527,000
TOTAL	$39,163,000

Using historical cost

AC Intertie	Approximate Length (Miles)	Estimated Cost per Mile (2012 $)	Year Built
Emmonak - Alakanuk	11	$407,000	2011
Toksook Bay - Tununak	6.6	$352,000	2006
New Stuyahok - Ekwok	8	$387,000	2007
Nightmute - Toksook Bay	18.04	$408,000	2009
Bethel - Napakiak	10.5	$313,000	2010
Average Estimated Cost per Mile		$373,000	
Estimated Cost for 60-mile Intertie		$22,404,000	

AC Intertie Cost Range	
Intertie and Substation Cost (Low Estimate)	$22,404,000
Intertie and Substation Cost (High Estimate)	$39,164,000
Intertie and Substation Cost per Mile (Low Estimate)	$373,000
Intertie and Substation Cost per Mile (High Estimate)	$653,000

HVDC Monopolar 2-Wire Intertie Estimated Cost with Difficult Terrain and Different Converter Station Cost Assumptions

COST CATEGORY	EPRI	$250,000 - 10% per 1 MW Converter	$250,000 + 10% per 1 MW Converter	$1.04 million for each Converter
Pre-construction	$5,928,000	$5,928,000	$5,928,000	$5,928,000
Administration/Management	$2,020,000	$2,020,000	$2,020,000	$2,020,000
Materials	$2,820,000	$2,820,000	$2,820,000	$2,820,000
Shipping	$1,374,000	$1,374,000	$1,374,000	$1,374,000
Mobilization/Demobilization	$5,165,000	$5,165,000	$5,165,000	$5,165,000
Labor	$4,260,000	$4,260,000	$4,260,000	$4,260,000
Additional Cost due to Difficult Terrain	$1,202,000	$1,202,000	$1,202,000	$1,202,000
Converter Station Construction	$3,415,000	$3,413,000	$4,813,000	$2,080,000
Contingency (20%)	$5,237,000	$5,236,000	$5,516,000	$4,970,000
TOTAL	$31,421,000	$31,419,000	$33,099,000	$29,819,000

HVDC Monopolar Two-Wire Intertie Estimated Cost Range	
Intertie and Converter Station Cost (Low Estimate)	$29,819,000
Intertie and Converter Station Cost (High Estimate)	$33,098,000
Intertie and Converter Station Cost per Mile (Low Estimate)	$497,000
Intertie and Converter Station Cost per Mile (High Estimate)	$552,000

HVDC Monopolar SWER Intertie Estimated Costs with Difficult Terrain and Different Converter Station Cost Assumptions

COST CATEGORY	EPRI	$250,000 - 10% per 1 MW converter	$250,000 + 10% per 1 MW converter	$1.04 million for each converter
Pre-construction	$6,019,000	$6,019,000	$6,019,000	$6,019,000
Administration/Management	$1,780,000	$1,780,000	$1,780,000	$1,780,000
Materials	$2,880,000	$2,880,000	$2,880,000	$2,880,000
Shipping	$824,000	$824,000	$824,000	$824,000
Mobilization/Demobilization	$2,033,000	$2,033,000	$2,033,000	$2,033,000
Labor	$4,020,000	$4,020,000	$4,020,000	$4,020,000
Additional Cost due to Difficult Terrain	$921,000	$921,000	$921,000	$921,000
Converter Station Construction	$2,772,000	$3,413,000	$4,813,000	$2,080,000
Contingency (20%)	$4,250,000	$4,378,000	$4,658,000	$4,111,000
TOTAL	$25,499,000	$26,268,000	$27,948,000	$24,668,000

HVDC Monopolar SWER Intertie Estimated Cost Range	
Intertie and Converter Station Cost (Low Estimate)	$24,668,000
Intertie and Converter Station Cost (High Estimate)	$27,948,000
Intertie and Converter Station Cost per Mile (Low Estimate)	$411,000
Intertie and Converter Station Cost per Mile (High Estimate)	$466,000

Intertie Cost Range		
Type of Intertie	Total Cost	Per Mile Cost
AC Cost – Low Estimate	$22,404,000	$373,000
AC Cost – High Estimate	$39,164,000	$653,000
HVDC Monopolar 2-wire Cost – Low Estimate	$29,819,000	$497,000
HVDC Monopolar 2-wire Cost – High Estimate	$33,098,000	$552,000
HVDC SWER Cost – Low Estimate	$24,668,000	$411,000
HVDC SWER Cost – High Estimate	$27,948,000	$466,000

Estimated Life-Cycle Cost Analysis for the Interties			
Parameter	AC Intertie	HVDC 2-Wire Monopolar	HVDC Monopolar SWER
Annual Transmission Losses in Converters and Transmission Lines (kWh)	2,422,000	2,739,000	2,588,000
Annual Value of Transmission Losses ($)	$391,000	$443,000	$418,000
Intertie Annual O&M Cost	$96,000	$139,000	$130,000
Project Life (years)	20	20	20
Discount Rate	3%	3%	3%
Present Value of Transmission Loss	$5,823,000	$6,585,000	$6,222,000
Present Value of O&M	$1,428,000	$2,071,000	$1,928,000
Intertie + Converter Station Cost ($ - low value)	$22,404,000	$29,819,000	$24,668,000
Intertie + Converter Station Cost ($ - medium value)	$30,784,000	$31,459,000	$26,308,000
Intertie + Converter Station Cost ($ - high value)	$39,164,000	$33,098,000	$27,947,000

Intertie + Converter Station Cost (low cost)			
	AC Intertie	HVDC 2-Wire Monopolar	HVDC Monopolar SWER
Estimated Life-Cycle Cost	$29,655,000	$38,475,000	$32,818,000
HVDC Life-Cycle Cost as a Percentage of AC Life-Cycle Cost		130%	111%
Present Value of Savings (Cost) for HVDC Compare to AC		($8,820,000)	($3,163,000)
Intertie + Converter Station Cost (medium cost)			
	AC Intertie	HVDC 2-Wire Monopolar	HVDC Monopolar SWER
Estimated Life-Cycle Cost	$38,035,000	$40,115,000	$34,458,000
HVDC Life-Cycle Cost as a Percentage of AC Life-Cycle Cost		105%	91%
Present Value of Savings (Cost) for HVDC Compare to AC		($2,080,000)	$3,577,000
Intertie + Converter Station Cost (high cost)			
	AC Intertie	HVDC 2-Wire Monopolar	HVDC Monopolar SWER
Estimated Life-Cycle Cost	$46,415,000	$41,754,000	$36,097,000
HVDC Life-Cycle Cost as a Percentage of AC Life-Cycle Cost		90%	78%
Present Value of Savings (Cost) for HVDC Compare to AC		$4,661,000	$10,319,000

Thank you! Any Questions?

http://energy-alaska.wikidot.com

- Jason Meyer

  Program Manager

  Emerging Energy Technology

  Alaska Center for Energy and Power

  University of Alaska, Fairbanks

  jason.meyer@alaska.edu

- Sohrab Pathan

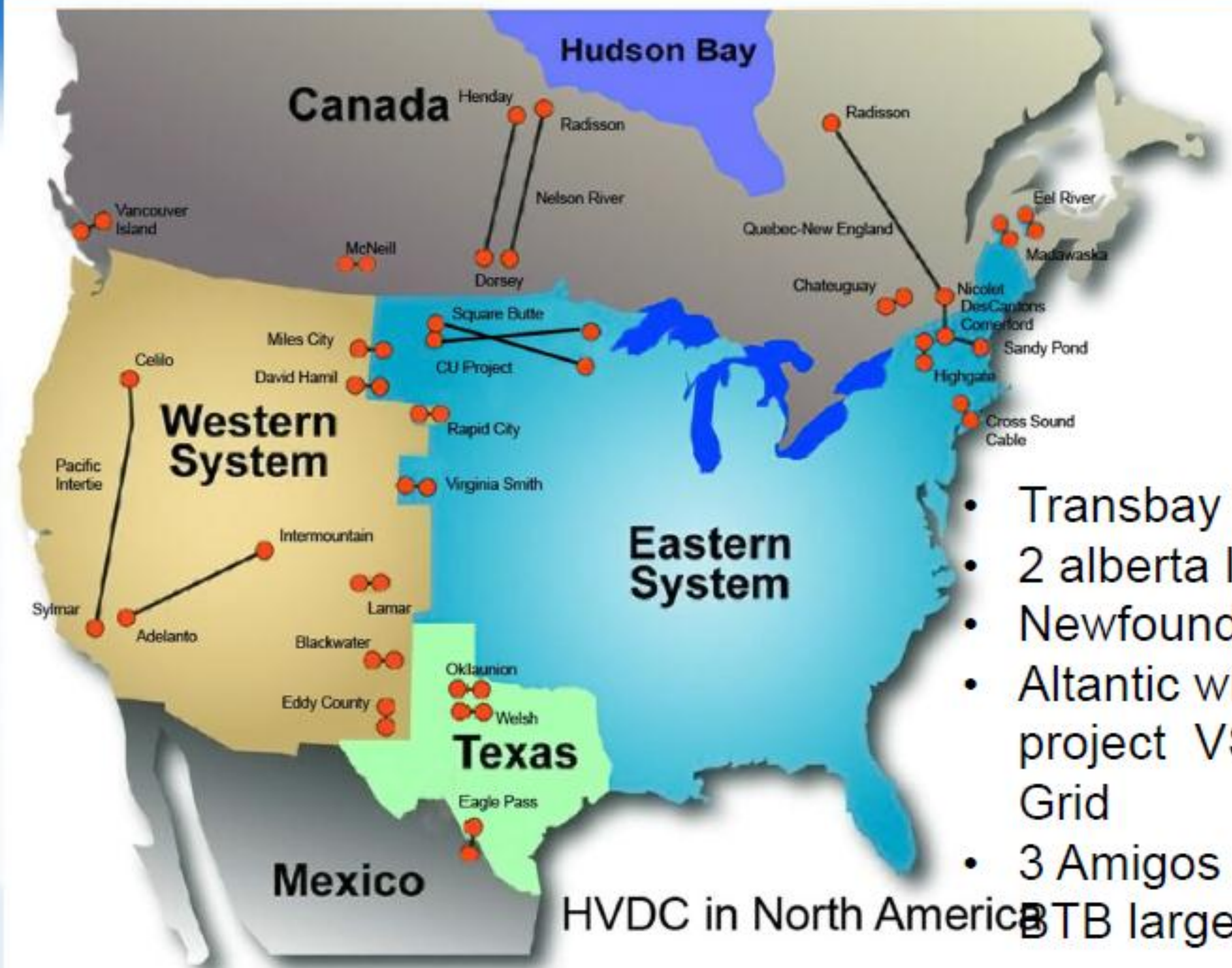
  Energy Economist

  Institute of Social and Economic Research

  University of Alaska, Anchorage

  ahpathan@uaa.alaska.edu

Extra Slides



HVDC in North America

- Transbay VSC
- 2 alberta links
- Newfoundland
- Altantic wind project VSC Grid
- 3 Amigos VSC BTB large

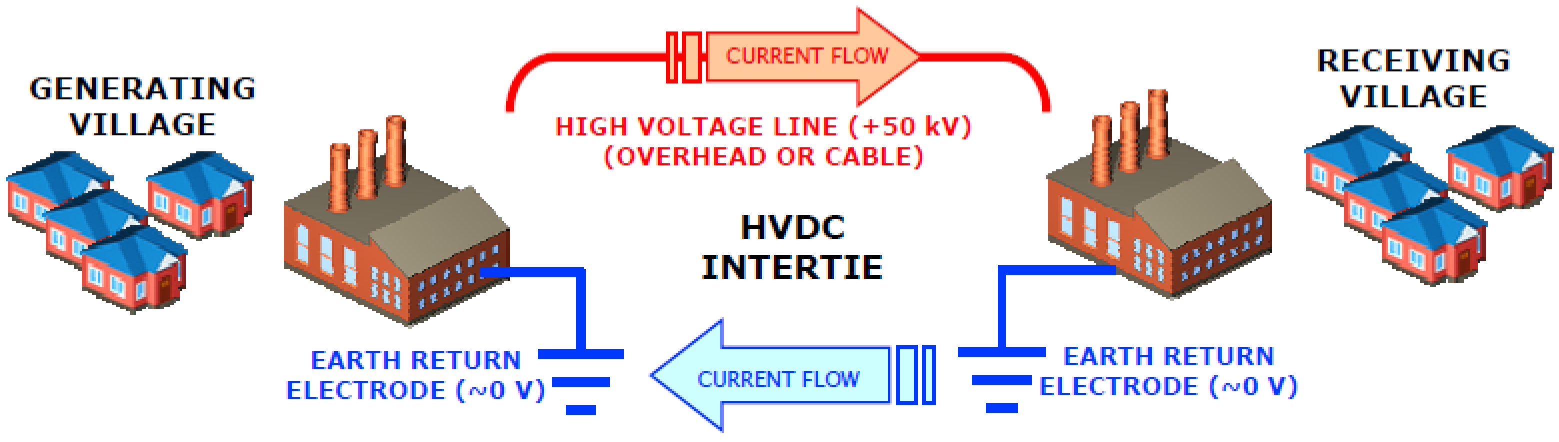


Figure 4-1: Monopolar HVDC Intertie Using SWER

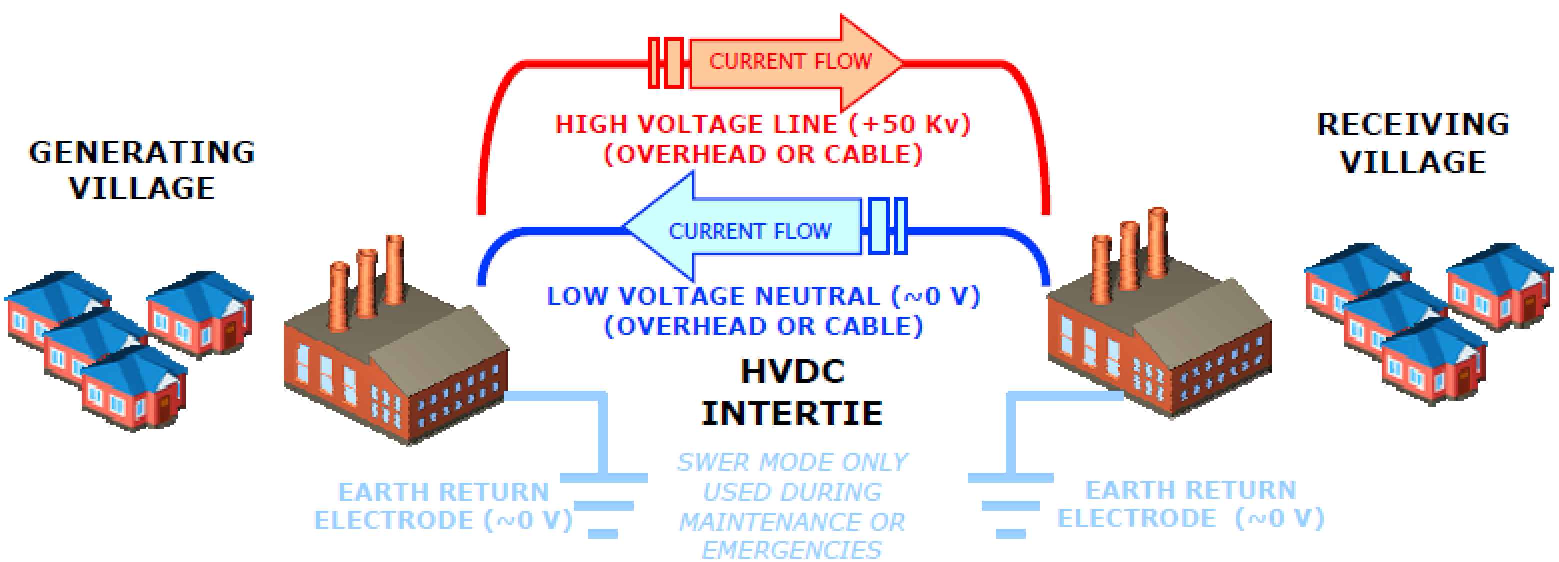


Figure 4-2: Monopolar HVDC Intertie With Return Conductor (SWER-capable for backup)

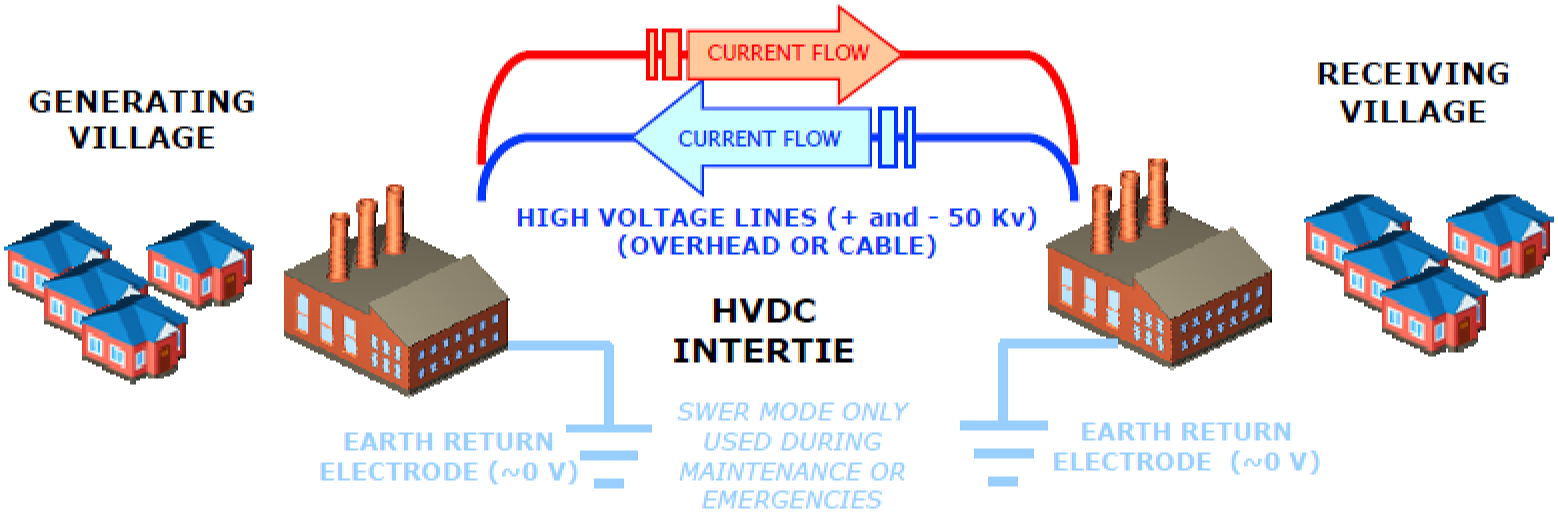
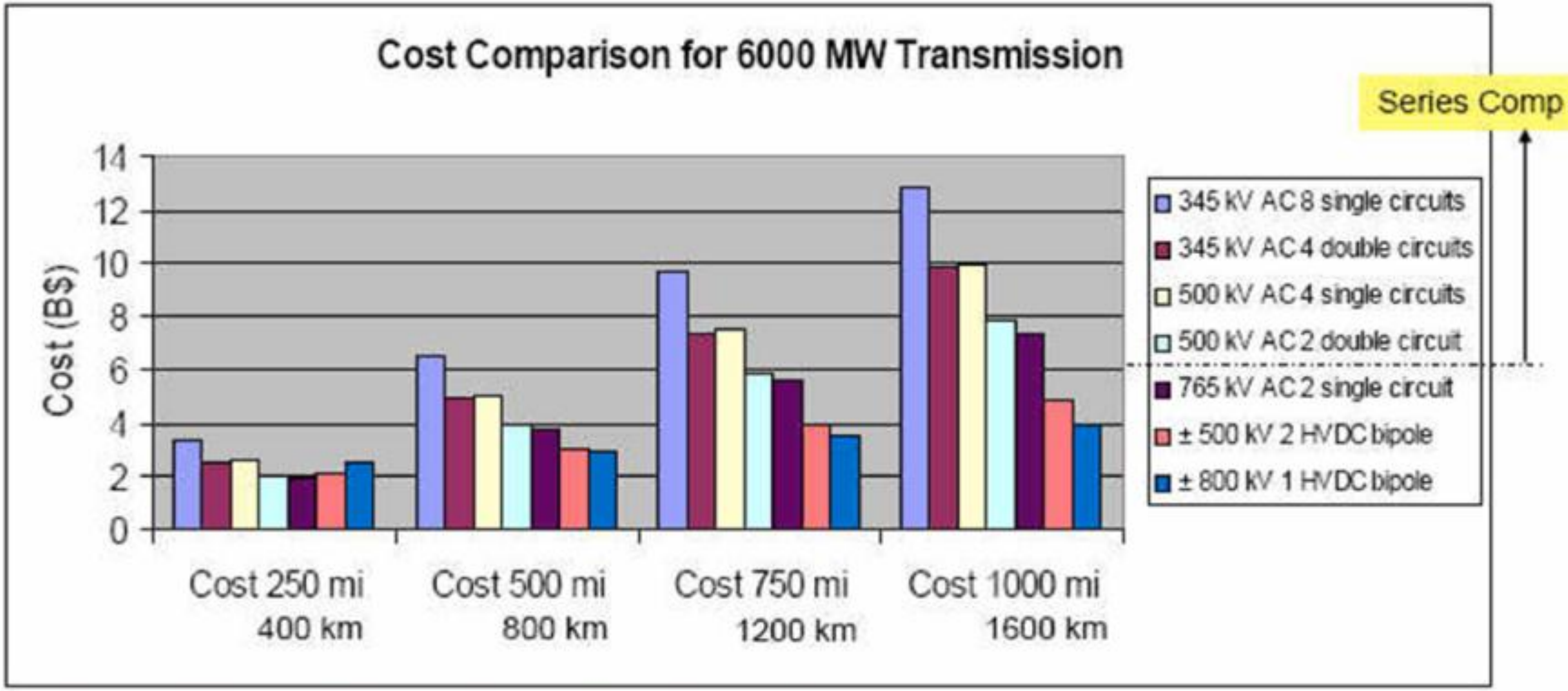


Figure 4-3: Bipolar HVDC Intertie (SWER-capable for backup)

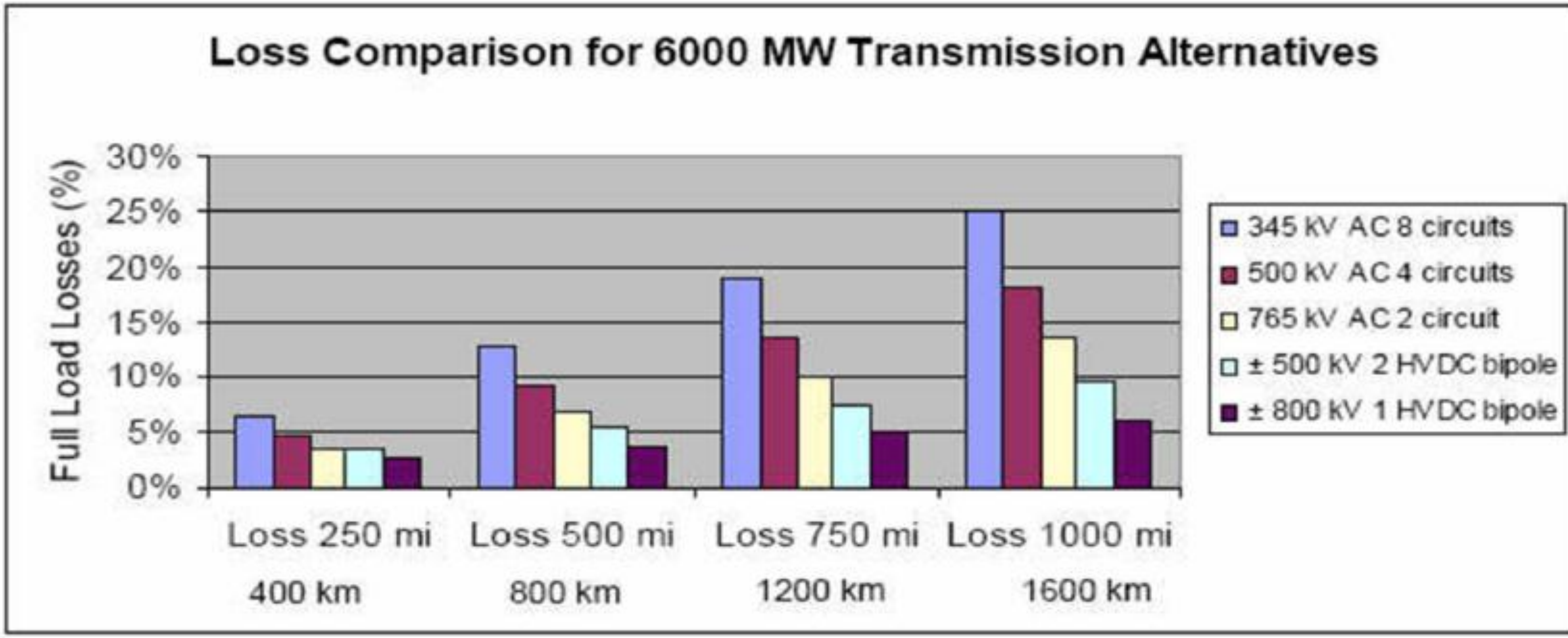
Comparative costs for 6000 MW transmission
Intermediate S/S and reactive comp every 400 km



Note: Series compensated ac lines loaded to ~ 2 x SIL,
765 kV loaded to ~ 1.3 x SIL or ~ steady state stability limit for 400 km line segment

Note: Transmission line and substation costs based on Frontier Line transmission subcommittee and NTAC unit cost data.

Transmission Alternatives Loss Comparison



Note: AC and DC line conductors chosen for comparable current densities, higher no. conductor bundles for higher voltages, more sub-conductors for 765 kV required for higher altitudes using same design criteria

ABB

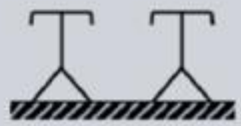
Existing systems with limitations for 5,000 MW power transfer over long distances

SIEMENS

~ HVAC 765 kV

- Limited suitability for point-to-point connections
- High power losses
- 2-3 lines required for 5,000 MW
- Limited to approx. 1,500 km

= HVDC 500 kV



- + Lower power losses than AC
- − Limited to 500 kV; 3,000 MW
- − Two lines needed for 5,000 MW
- − Not optimized for investment and operational costs

HVDC at 800 kV for economical, long-distance power transmission

SIEMENS

= HVDC 800 kV

- Very high power capacity (5,000 MW and higher) of a single system
- 25% lower transmission cost compared to 500 kV HVDC
- Smaller footprint and lower overhead transmission line costs - only one bipole needed